MASS EXCHANGE BETWEEN HAMILTON HARBOUR AND LAKE ONTARIO

September 1975

Ministry of the Environment

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SUMMARY

The mass exchange between Hamilton Harbour and Lake Ontario, through the Burlington Canal, was considered important in estimating dissolved oxygen budget of the harbour. A lake-harbour exchange computational method was developed to utilize the current meter data (September 1-13, 1975) at two levels on a single tower. During the study period, the canal water was found to be quasi-isothermal; consequently unidirectional flow existed.

It was estimated that an average of $2.14 \times 10^6\ m^3.d^{-1}$ ($25\ m^3.s^{-1}$) of harbour water flowed into the lake, while $0.77 \times 10^6\ m^3.d^{-1}$ ($8\ m^3.s^{-1}$) of lake water flowed towards the harbour. This accounts for the total and net daily exchange of 1.04% and 0.50% of harbour volume with net exchange being towards the lake. As more water leaves than enters the harbour, the lake-harbour exchange is considered important for maintaining and even improving the existing harbour water quality. The harbour dilution factor was estimated as 0.0019 per day.

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INTRODUCTION

Hamilton Harbour is a natural harbour of fresh water in the north western corner of Lake Ontario. It is triangular shaped, 8 × 5 km, with a mean depth of 13 m (see Figure 1) and a water volume of 2.8×10^8 m^3. The harbour is connected to the lake by the Burlington Canal which is approximately 820 m × 107 m wide × 9.5 m deep. Several creeks drain into the harbour with mean daily flow of 0.35×10^6 m^3 consequently, the natural throughput is approximately 0.12 percent of the total harbour volume per day. The Hamilton and Burlington water pollution control plants discharge a total of 3.2 $m^3.s^{-1}$ of treated effluents. Together with the natural flow, this results in a total throughput of 0.22 percent of the harbour volume per day. The major industries located on the south shores of the harbour use and recirculate 27 $m^3.s^{-1}$ of harbour water (MOE, 1974).

The harbour is hypertrophic, with mean chlorophyll a 20 $\mu g.\ell^{-1}$ and total phosphorus 40 to 200 $\mu g.\ell^{-1}$. During the summer, the deeper waters of hypolimnion experience severe oxygen depletion. The lake-harbour exchange is important in determining a dissolved oxygen (DO) budget for the harbour. Based upon current measurements in the Burlington Canal, Palmer and Poulton (1976) stated that the mean exchange is of the order of 1% of the harbour volume per day. In the summer, volumetric exchange of 1% of the harbour volume per day accounts for 19% of the DO input to the harbour (Polak and Haffner, 1977).

THEORY

Freeman et al (1974) found the lake-harbour exchange is partly due to the Helmholtz mode, and van de Kreeke (1976) has shown that harbours with restricted entrances such as Hamilton Harbour have faster currents in the entrance due to the restriction. Helmholtz resonance is a balance between the kinetic energy of the flow through the canal and the potential energy due to the change in water level within the harbour. The kinetic energy of the flow through the canal causes a unidirectional open channel flow. Dick and Marsalek (1973) attributed the exchange to:

(a) Unidirectional flow in the canal caused by the Helmholtz mode (difference in lake and water levels).

(b) Densimetric flow caused by the thermal stratification; warm harbour water flowing to the lake in the top layer and colder lake water flowing to the harbour in the bottom layer, underneath the warmer water.

The unidirectional flow due to Halmholtz mode, persists while the densimetric flow occurs in the summer season only. The analysis by Dick and Marsalek (1973) showed that the unidirectional flow is the major source of mass exchange through the Burlington Canal.

As the exchange process is complex and variable, only estimates of the exchange volume are possible. Better methods can be formulated for a better data set consisting of current and temperature profiles in the vertical and horizontal plane at three cross-sections. In the absence of such data, an episode method is presented using current measurements from a single tower at two different depths.

Currents are known to be generally homogenous across the channel except for the wall boundary layers (about 2 m from the wall). The data may, therefore, be transposed to the middle of the channel. The method outlined below applies to the isothermal case only (as determined by bathycasts and temperature measurements) when current speed profile with depth approaches parabolic distribution, expressed as;

$$U^2 = kY \quad \ldots\ldots \quad (1)$$

where:

U is the velocity along the channel axis at a depth Y from bottom.

k is a constant

Utilizing the average current speed at two depths (6.1 m and 7.5 m from bottom in 9.5 m of water), it can be shown that the mean current speed of the vertical cross-section is 80% of the average measured at the two levels. Let $\overline{U}_1$ be the mean current speed persisting towards the harbour for time t_1 and let the water particle travel an excursion distance $\overline{X}_1$ towards the harbour in time t_1, such that:

$$\overline{X}_1 = \overline{U}_1 \times t_1 \quad \ldots\ldots \quad (2)$$

Then the corresponding flow (towards the harbour) q_1 through the cross-section is:

$$q_1 = 0.8 \times \overline{U}_1 \times A \times t_1 \quad \ldots\ldots \quad (3)$$

where A = cross-sectional area of the channel.

The water movement may now reverse its direction due to Helmholtz mode. Let $\overline{U}_2$ be the mean current speed persisting

towards the lake for a time t_2 and let the water particle travel an excursion distance $\overline{X}_2$ towards the lake in time t_2, such that:

$$\overline{X}_2 = \overline{U}_2 \times t_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Then the corresponding flow (towards the lake) q_2 through the cross-section is:

$$q_2 = 0.8 \times \overline{U}_2 \times A \times t_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The excursion distances, lying between 50 and 1100 m, were divided into 50 m classes upto 400 m (about half the channel length) and into 100 m classes for excursions greater than 400 m. The mean of these classes E_i were ranked with E_1 being the maximum (E_1 = 1050 m). For each E_i, the flows q_1 and q_2 are grouped and summed, such that:

For i = 1 to n

$$H_i = \Sigma\, q_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$L_i = \Sigma\, q_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

$$T_i = H_i + L_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where:

H_i is the total flow towards the harbour,
L_i is the total flow towards the lake
T_i is the total exchange through the canal.

The above flows are then accumulated as:

$$Hq_i = \sum_{i=1}^{i} H_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

$$Lq_i = \sum_{i=1}^{i} L_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

$$Tq_i = Hq_i + Lq_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

A critical excursion distance E_c can be evaluated by the dissolved solid (DS) budget as well as the plot of E_i against T_i. It will be shown that the flows, corresponding to excursion distance less than E_c, do not contribute to the mass exchange.

$$\text{Therefore, for} \quad \left.\begin{array}{lll} i & = c & \\ \text{and} \quad E_i & = E_c & \\ Q_1 & = Hq_i & = Hq_c \\ Q_2 & = Lq_i & = Lq_c \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (12)$$

where Q_1 and Q_2 are total flows towards the harbour and lake respectively.

Equations (9), (10) and (11) yield accumulated or total flows when flows corresponding to excursion distances less than E_i are neglected.

It is apparent that the mass exchange through the canal results in dilution of conservative contaminants (e.g. dissolved solids). Such a dilution factor may be computed as:

$$D = (C_h - (C_{im} + C_\ell))/(0.5 \times (W_1+W_2) \times p) \quad \ldots\ldots \quad (13)$$

where:

D = Dilution factor per day

C_h = Estimated mass of conservative contaminant transferred from the harbour to the lake by the exchange process during p days.

C_ℓ = Estimated mass of conservative contaminant transferred from the lake to the harbour by the exchange process during p days.

C_{im} = Estimated mass of conservative contaminant added to the harbour by the industrial and municipal discharges during p days.

W_1 = Estimated mass of conservative contaminant present in the harbour, initially.

W_2 = Estimated mass of conservative contaminant present in the harbour after p days.

METHOD

Two self-recording current instruments were operated at 6.1 m and 7.5 m from bottom on a single tower in Burlington Canal (9.5 m total depth) from 14 August to 13 September, 1975. As the compasses of the Geodyne-type instruments have historically malfunctioned in the Burlington Canal, only Plassey current instruments (Model MO 21) were deployed. Prior to the installation, the instruments were calibrated and checked in the laboratory and set to record current directions, water temperature and current magnitudes (speed integrated over 10 min.) every 10 minutes.

DATA ANALYSIS

Water temperature and current speed data were pre-whitened (numerically smoothed) after Blackman and Tukey (1959; p.29, 39, 174) using binomial weights after Panofsky and Brier (1968; p.150) as follows:

$$C_m = N! \,/(m! \; (N-m)!) \qquad (14)$$

where Cm is the binomial coefficient and these converge on the shape of the normal distribution curve as N increases.

For the present data at 10 minute intervals, N = 4 results in the best smoothing. The binomal weights are then computed as:

$$S_m = C_m / \sum_{o}^{m} C_m \quad \ldots\ldots \quad (15)$$

where S_m are the binomial weights for smoothing the data. The current directions were not smoothed as the water flow was restricted along the canal axis. The data were divided into monthly records for August and September.

Water Temperature

Figure 2 shows two bathythermograph casts in the Burlington Canal on August 15 and September 5, 1975. Thermal stratification on August 15 is extensive while conditions appear to be approaching isothermal on September 5, 1975. During August, thermal stratification existed in the canal creating a thermal lense. During thermal stratification, water movement data at four or more different depths are considered necessary to compute mass exchange as water may be moving in opposite direction at different levels. The available data at two levels (1.4 m apart vertically) were therefore not sufficient to compute mass exchange when stratification existed. The September data during nearly isothermal (unidirectional open-channel flow) conditions were processed for the computation of mass exchange as follows.

The frequencies of occurrence for hourly temperature values were computed at both levels along with mean, standard deviation, maximum and minimum. These statistics are presented in Table 1. A simple correlation coefficient between the two temperature series was computed to be 0.81 and χ^2 for the two series was computed to be 11.60 with 11 degrees of freedom (see Table 1). As $\chi^2_{0.95,11} = 19.68 > \chi^2_{11} = 11.60$, it was concluded that temperatures at the two levels were not significantly different providing verification of quasi-isothermal conditions. The computer plotting of currents at both levels (see Fig. 4) indicated that the flows were in approximate phase, consequently the quasi-isothermal conditions prevailed in the Burlington

Canal. Cross-correlations of water temperatures between two levels were calculated for up to 30 h lags and is presented in Table 2. The mean temperature at upper and lower levels was 20.5^{o}C and 19.8^{o}C respectively with standard deviations of 1.8^{o}C and 2.3^{o}C.

Water Movements

Two dimensional frequency of occurrence of current magnitude and direction at both levels were computed and tabulated (see Appendix for details). Table 3 presents a summary of statistical results. At both levels, the resultant currents during September were going towards the lake. The resultant speed at the upper level was 3.27 cm.s^{-1} while at the lower level it was 1.76 cm.s^{-1}. The arithmatic average speed at both levels was approximately 8 cm.s^{-1} while the maximum speed recorded at both levels was just under 45 cm.s^{-1}. The persistence factor at upper level was higher (0.40) than at the lower level (0.22).

The smoothed current speeds were resolved along and across the canal and then averaged over an hour. The hourly values of speed and temperature were subjected to the spectral analysis (see Table 4) by standard numberical techniques and the Hanning of the coefficients after Blackman and Tukey (1959; p.34, 171). Cross-coherences between currents and water temperatures between the two levels were computed and significant coherences (95% confidence) are summarized in Table 5.

Exchange Calculations

As the currents going towards the channel wall do not contribute to the flow, all currents falling in the shaded area of Figure 3 were neglected. Water movements in the shaded area ranged from 3 ato 10% of the time. These few instances may be due to the instantaneous direction readings

recorded by the Plessey instruments. Normally, the water movements in the canal should be parallel to the axis of the channel. The rest of the currents at both levels (90-97%) were then resolved along the channel axis.

The resolved speeds were then computer plotted for both levels (see example in Figure 4). Points to the left of the Zero Speed Line (ZSL) indicates flows towards the harbour while the points to the right of the ZSL show flow towards the lake. The date and time are also printed. When currents are mainly towards the walls, no points are printed during that interval. The points on the printout were then joined manually, the dotted lines indicate interpolation in the absence of one or more data points. Figure 4 shows that the two instruments recorded flows in approximate phase. As expected, the flows shift to and from the harbour each time the time history plot intersects the ZSL (see Figure 4). Between two such convective crossings, the flow persists in one direction. Now, if the average speed during such an interval is computed and a time interval noted, it is possible to calculate the excursion distance ($\overline{X}_1$ or $\overline{X}_2$) a particle may travel during that episode. The volume of such flow (q_1 or q_2) can be calculated from equations (3) or (5) and are presented in Appendix. This process was repeated for the complete record of 13 days. Computations according to equations (6) to (11) were carried out and tabulated in Table 6. Thus, total flows toward the harbour and toward the lake were calculated for a period of 13 days for all excursion distances. Flow through the canal for different excursion distances is also presented in Figure 5 showing that small excursions (<325 m) are responsible for a maximum of 16% of the total exchange through the canal. However, the small excursions cause water to move within the confines of the canal length and never leave the canal. Therefore, these small excursions are responsible for exchange much less than the indicated 16% of the total. Thus, flows associated with small excursions (<325 m) are neglected in

the final estimates. A summary of exchange results is presented in Table 9. During the first 13 days of September 1975, the average flow rate of water from the lake to the harbour was 0.8×10^6 $m^3.d^{-1}$ or 9 $m^3.s^{-1}$ while the average flow rate of water from the harbour to the lake was 2.1×10^6 $m^3.d^{-1}$ or 25 $m^3.s^{-1}$. This represented a total exchange rate of 2.9×10^6 $m^3.d^{-1}$ or 34 $m^3.s^{-1}$ (1% of the harbour volume per day). The mass exchange for the harbour is schemetically presented in Figure 6.

Dissolved Solids Budget

The dissolved solids (DS) mass in the harbour were estimated for August 15 and September 16, 1975, utilizing a modified Boyce (1973) method (Polak and Haffner, 1977) and the DS vertical profile at a number of stations in the harbour (see Figure 1). Dissolved solids were comuted as 0.65 × conductivity. The harbour was divided into 500 x 500 m cells each having constant depth. All cells were divided into one metre layers down to the bottom. The nearest DS profile to a cell was utilized to compute the DS content of the layer and the cell. The contents of all layers and cells were then summed for the total content of the harbour (W_1 in equation (13)). Similarly, the content of the harbour after 32 days was also estimated (W_2 in equation (13)).

The total DS added to the harbour during the 32 days (August 15 to September 16) were estimated from industrial and municipal discharge data. Similarly, the DS addition (or reduction) to the harbour due to mass exchange was computed. The results of the above computations are presented in tables 7 and 8 indicating that the mass balance of DS can be approximately achieved if flows corresponding to excursions less than 325 m are neglected.

Knowing the average values of DS in the harbour as well as in the lake (just outside the Burlington Canal on either

side) and the estimated flows in the canal in either direction, it is possible to calculate C_ℓ and C_h of equation (13). C_{im}, W_1 and W_2 had previously been estimated for 32 (P) days. Using these values in equation (13), the dilution factor D was computed to be 0.0019 per day.

DISCUSSION

Water Temperature

Chi-square testing for temperatures at two levels showed homogeniety. Table 2 lists cross correlations of temperatures between two levels for up to 30 h lags. At zero lag, the correlation coefficient was 0.81. Cross-coherence of temperatures between the two levels indicate significant coherences for 15.0, 17.1 and 40.0 to 125.0 h. The average temperatures at both levels were plotted (see Appendix for some examples) every two hours and these graphs confirmed the isothermal conditions in the canal. It may therefore be concluded that quasi-isothermal conditions prevailed in the Burlington Canal and consequently an unidirectional flow regime existed.

Water Movements

At both levels, the resulting currents moved towards the lake. The currents were negligible (< 0.3 cm.s^{-1}) for 20% of the recording period. Water movements were towards the lake (resultant direction) for 28% of the time while towards the harbour (opposite to the resultant direction) for 7% of the time indicating the net water movement towards the lake.

Autospectra of Water Movements and Temperature

Autospectral analysis of the currents (Table 4) indicates similar significant periods at both levels. The 12.0 h period may be related to the semidiurnal or tidal motions

and this periodicity occurs at both levels along the canal axis and at the upper level only across the canal axis. The 12.1 h period for the temperature (composite value at upper and lower levels) indicates the semi-diurnal or tidal effects on water temperatures. A period of 10.9 h was observed in the temperatues at the upper level and this may be due to the lakewide effects. Kohli and Palmer (1973) found similar periodicities at Lakeview, Lake Ontario. The first mode of Lake Ontario oscillations (5.0 h) is observed in the Burlington Canal at both levels for currents as well as water temperatures. Rao and Schwab (1974) computed the first mode of oscillations for Lake Ontario as 5.11 h while Rockwell (1966) obtained a value of 4.91 h. The second mode (3.11 h) as computed by Rao and Schwab (1974) may be observed as 3.2 h in the currents and temperatures at the upper level (Table 4). The period of 2.4 h observed in the current along the canal axes at both levels and for temperatures at the upper level may be due to the third free oscillations of Lake Ontario (Rockwell, 1966 and Rao and Schwab, 1974), Helmholtz mode for Hamilton Harbour (Freeman et al, 1974), or a resonant cooscillation involving both.

The periodicities of the measured data relate to the theoretical lake, harbour and Helmholtz periodicities, confirming that the data set used for the mass exchange computation portrays the expected periodic motion.

Mass Exchange

There exists a critical excursion distance below which the water movements in the canal do not clear the confines of the channel. In order to evalute such a critical excursion distance, a DS budget for the harbour was computed. Table 7 shows that during the 32 days (August 15 to September 16, 1975), 12872 T of DS must leave the harbour through the Burlington Canal. Table 8 shows that the maximum (11625 T) amount of DS moves through the canal from the harbour to the

lake if the flows corresponding to excursions <325 m are ignored. Thus, the critical excursion distance may be about 325 m. This critical distance was also confirmed by Figure 5 which showed the excursions <325 m may, at the most, contribute 16% of the total flow. Based on a critical excursion distance of 325 m, average flow towards the harbour was 9 $m^3.s^{-1}$ (0.27% of harbour volume per day) while towards the lake, it was 25 $m^3.s^{-1}$ (0.77% of harbour volume per day). This resulted in a total mass exchange of 34 $m^3.s^{-1}$ or 1.04% of harbour volume per day (see Table 9). The net flow towards the lake was, therefore, 16 $m^3.s^{-1}$ or 0.5% of harbour volume per day. The mass exchange resulted in a dilution factor of 0.0019 per day; consequently the water quality in the harbour may improve.

During the period of no thermal stratification, (September 26 to October 6, 1973), Palmer and Poulton (1976) estimated a net exchange of 1% of the harbour volume per day towards the lake and a total mass exchange of 3% of the harbour volume per day. These results are similar to the present study but larger in magnitudes. The larger flow estimates of Palmer and Poulton (1976) may be attributed to their computational method (based on the arithmetic mean values). The present episode method yielded relatively better flow estimates as checked by the DS budget.

CONCLUSIONS

The mass exchange between Lake Ontario and Hamilton Harbour through Burlington Canal was found to be a complex process. Unidirectional flow and unstratified water in the canal were the basic assumptions of the present study which was based on data for September, 1975. It is estimated that on the average 2.14 x 10^6 $m^3.d^{-1}$ of harbour water flowed into the lake, while 0.77 x 10^6 $m^3.d^{-1}$ of lake water flowed into the harbour. This accounts for a total exchange of 1.04% of harbour volume per day with a net exchange of 0.50% of the harbour volume per day towards the lake.

The lake harbour exchange resulted in a dilution of 0.0019 per day. This is very important for maintaining and even improving the existing water quality in the harbour because the harbour water, with its higher dissolved solids content, is discharged to the lake while better quality and oxygenated lake water flows into the harbour.

As the calculations for mass exchange were computed for 13 days only and since they are based on the simplifying assumptions of unidirectional flow, they provide only partial information for numerical modelling of the harbour and accounting for the dissolved oxygen stocks. Refinements would require collecting data for more points and under stratified conditions and possibly improving the computation technique.

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TABLE 1: Water Temperature Frequency, September 1975
Burlington Canal, Hamilton Harbour, Lake Ontario

Temperature Range °C	Upper Level %	Lower Level %
12.00 - 12.99	0.00	0.14
13.00 - 13.99	0.15	0.98
14.00 - 14.99	0.31	1.12
15.00 - 15.99	2.16	3.77
16.00 - 16.99	2.16	7.40
17.00 - 17.99	5.40	11.31
18.00 - 18.99	6.33	8.66
19.00 - 19.99	12.96	12.15
20.00 - 20.99	28.55	15.36
21.00 - 21.99	21.45	20.67
22.00 - 22.99	18.06	14.66
23.00 - 23.99	2.01	3.49
24.00 - 100.00	0.46	0.28
TOTAL	100.00	100.00
MEAN °C	20.48	19.85
STD DEV °C	1.78	2.28
MAX °C	24.48	24.06
MIN °C	13.77	12.87
SERIES LENGTH	660	718

Corelation Co-efficient = 0.81

$X^2_{11} = 11.60$

$X_{0.95,11} = 19.68$

∴ Temperatures at two levels are not statistically different.

TABLE 2: Cross-correlations Between Water Temperatures at Two Depths (Upper and Lower)

Lag (h)	Upper Leads Lower	Lower Leads Upper
0	0.812	0.812
1	0.800	0.807
2	0.804	0.800
3	0.801	0.809
4	0.791	0.806
5	0.785	0.783
6	0.786	0.774
7	0.783	0.772
8	0.774	0.764
9	0.768	0.762
10	0.755	0.765
11	0.755	0.755
12	0.761	0.747
13	0.756	0.757
14	0.741	0.763
15	0.730	0.759
16	0.724	0.742
17	0.719	0.731
18	0.718	0.726
19	0.710	0.722
20	0.697	0.724
21	0.687	0.717
22	0.686	0.706
23	0.684	0.702
24	0.679	0.707
25	0.666	0.708
26	0.648	0.701
27	0.650	0.696
28	0.657	0.692
29	0.648	0.695
30	0.633	0.702

TABLE 3: Summary of Current Statistics in Burlington Canal, Hamilton Harbour, Lake Ontario, September 1975

	UPPER LEVEL	LOWER LEVEL
Resultant direction coming from 0^{o} as north	252	255
Resultant speed (cm. s^{-1})	3.27	1.76
Average speed (cm. s^{-1})	8.23	7.94
Maximum speed (cm. s^{-1})	44.94	44.23
Persistence factor	0.40	0.22
Period of negligible* speed (% of recording period)	20	20
Percentage of time going in direction of resultant	37	19
Percentage of time going in direction opposite to resultant	7	7
Total number of readings	3925	4309
Interval of readings (mins)	10	10
Total depth of the Canal (m)	9.5	9.5
Depth of the meter operation from bottom (m)	7.5	6.1

* <0.3 cm. s^{-1}

TABLE 4: Summary of Major Spectral Periods (hours)
Burlington Canal, Hamilton Harbour
Lake Ontario
September 1975
80% Confidence Level

	Upper Level	Lower Level
Currents Along the Canal Axis	12.0*, 5.0*, 3.2*, 2.4, 2.3	12.0*, 5.0*, 3.4*, 2.4
Currents Across the Canal Axis	12.0*, 5.0*, 3.2	3.9
Temperature-Grand Mean	10.9*, 5.0*, 3.2*, 2.4, 2.2	13.3*, 5.5*, 3.3*

* 95% Confidence Level

TABLE 5: Summary of Coherences (95% Confidence)
Burlington Canal, September 1975

Upper (111A) and Lower (1110) Meter Locations

	Significant Periods (h)
Speed along the Canal	3.2
Speed across the Canal	NONE
Lower - speed along Canal and water temp	12.0-10.0,6.0-4.6,3.9-3.4,2.9
Lower - speed across Canal and water temp	NONE
Temp at Upper and Lower locations	120.0-40.0,17.1-15.0*

*90% Confidence

Table 6: Flow through Burlington Canal, Hamilton Harbour.

i	Mean Excursion Travelled E_i (m)	Flow x 10^3 m^3 to harbour H_i	to lake L_i	Exchange T_i	Accumulated Flow x 10^3 m^3 to harbour Hq_i	to lake Lq_i	Exchange Tq_i	Average Accumulated Flow/day x 10^6 $m^3.d^{-1}$ to harbour	to lake	Total Exchange
1	1050	0	2358	2358	0	2358	2358	0.00	0.18	0.18
2	950	0	1508	1508	0	3866	3866	0.00	0.30	0.30
3	850	661	1447	2108	661	5313	5974	0.05	0.41	0.46
4	750	1790	3053	4843	2451	8366	10817	0.19	0.64	0.83
5	650	2224	6387	8611	4675	14753	19428	0.36	1.14	1.50
6	550	864	3412	4276	5539	18165	23704	0.43	1.40	1.82
7	450	2507	6832	9339	8046	24907	33043	0.62	1.92	2.54
8	375	881	1554	2435	8927	26551	35478	0.69	2.04	2.73
9	325	1035	1330	2365	9962	27881	37843	0.77	2.15	2.91
10	275	1834	1110	2944	11796	28991	40787	0.91	2.23	3.14
11	225	1608	1695	3303	13404	30686	44090	1.03	2.36	3.39
12	175	1265	983	2248	14669	31669	46338	1.13	2.44	3.57
13	125	836	530	1366	15505	32199	47704	1.19	2.48	3.67
14	75	546	218	764	16051	32417	48468	1.24	2.49	3.73

Table 7: Dissolved Solids (DS) Budget Hamilton Harbour, August-September 1975.

Date		Total DS in Harbour
15 August 75		75049 T
16 September 75		73847 T
From 15 August to 16 September (32 days), net reduction of DS in harbour	=	1202 T
Addition of DS to harbour by industry	=	7424 T
Addition of DS to harbour by municipal effluents	=	4246 T
Total		12872 T

To achieve mass balance, 12872 T of DS must leave harbour through Burlington Canal and enter Lake Ontario, during the 32 days.

TABLE 8: Net Transfer of Dissolved Solids (DS) to Lake
August 15 - September 16, 1975.

Ei (m)	Net flow per day to lake x 10^6 m^3	Cumulative DS to lake in 32 days (T)
1050	0.18	1516
950	0.30	2527
850	0.36	3033
750	0.45	3791
650	0.78	6571
550	0.97	8171
450	1.30	10951
375	1.35	11372
325	1.38	11625
275	1.32	11120
225	1.33	11204
175	1.31	11035
125	1.29	10867
75	1.25	10530

Table 9: Summary of Mass Exchange Results Burlington Canal, Hamilton Harbour, Lake Ontario September 1-13, 1975.

For 13 days and excusions	> 325 m
Total flow into harbour	= 9.96 x 10^6 m^3
Total flow into lake	= 27.88 x 10^6 m^3
Total volume of Hamilton Harbour	= 2.80 x 10^8 m^3.
Average daily flow into harbour	= 0.77 x 10^6 $m^3.d^{-1}$
	= 8.87 $m^3.s^{-1}$
	= 0.27% of harbour volume per day
Average daily flow into lake	= 2.14 x 10^6 $m^3.d^{-1}$
	= 24.87 $m^3.s^{-1}$
	= 0.77% of harbour volume per day
Total daily exchange	= 2.91 x 10^6 $m^3.d^{-1}$
	= 33.69 $m^3.s^{-1}$
	= 1.04% of harbour volume per day

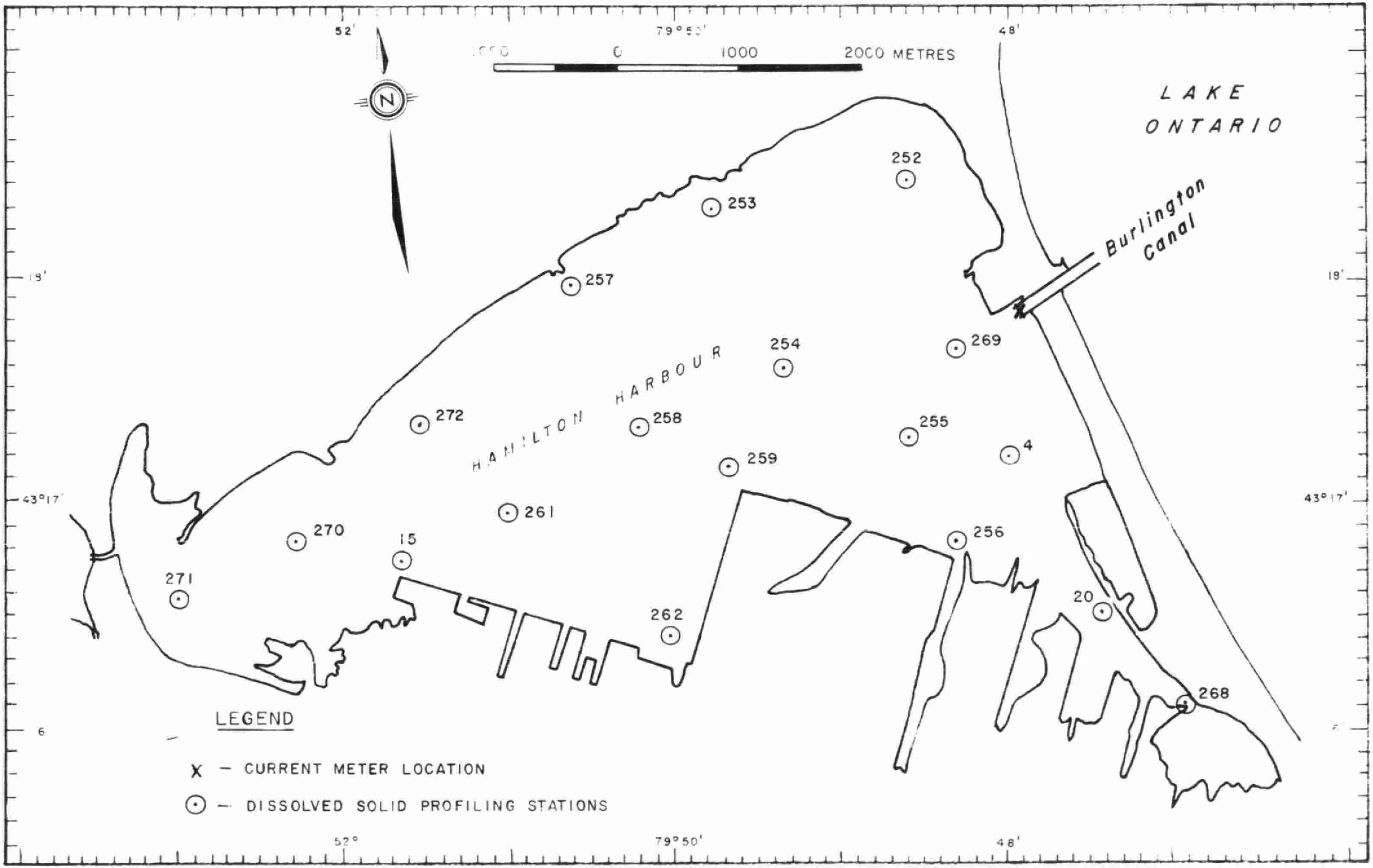
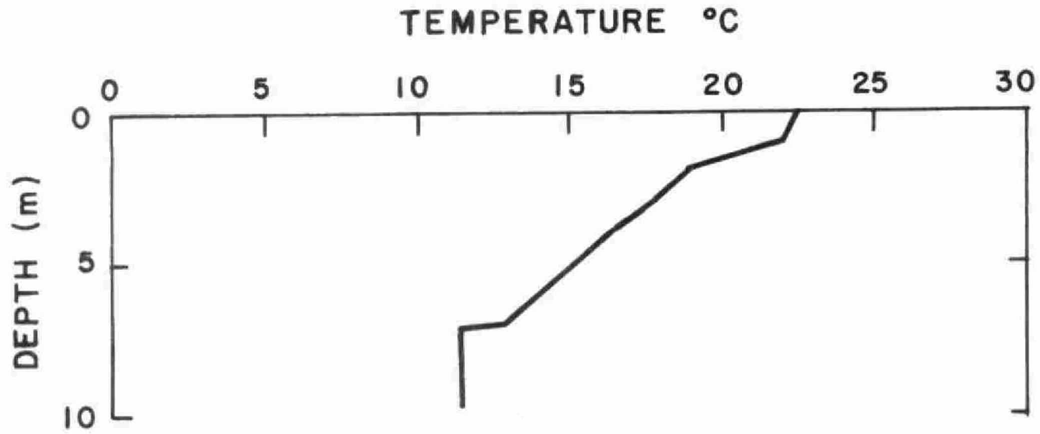
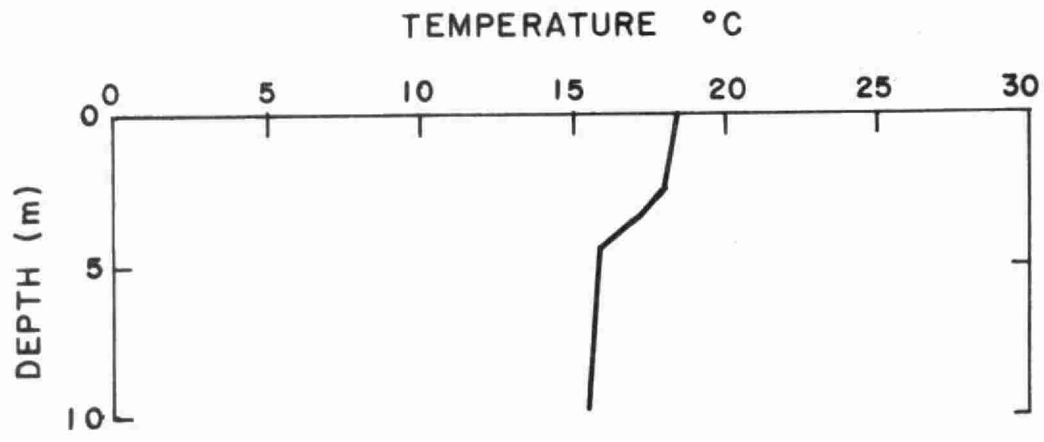


FIGURE 1: HAMILTON HARBOUR AND BURLINGTON CANAL



15 AUGUST, 1975



5 SEPTEMBER, 1975

FIGURE 2 : TEMPERATURE PROFILE BURLINGTON CANAL LAKE ONTARIO, 1975

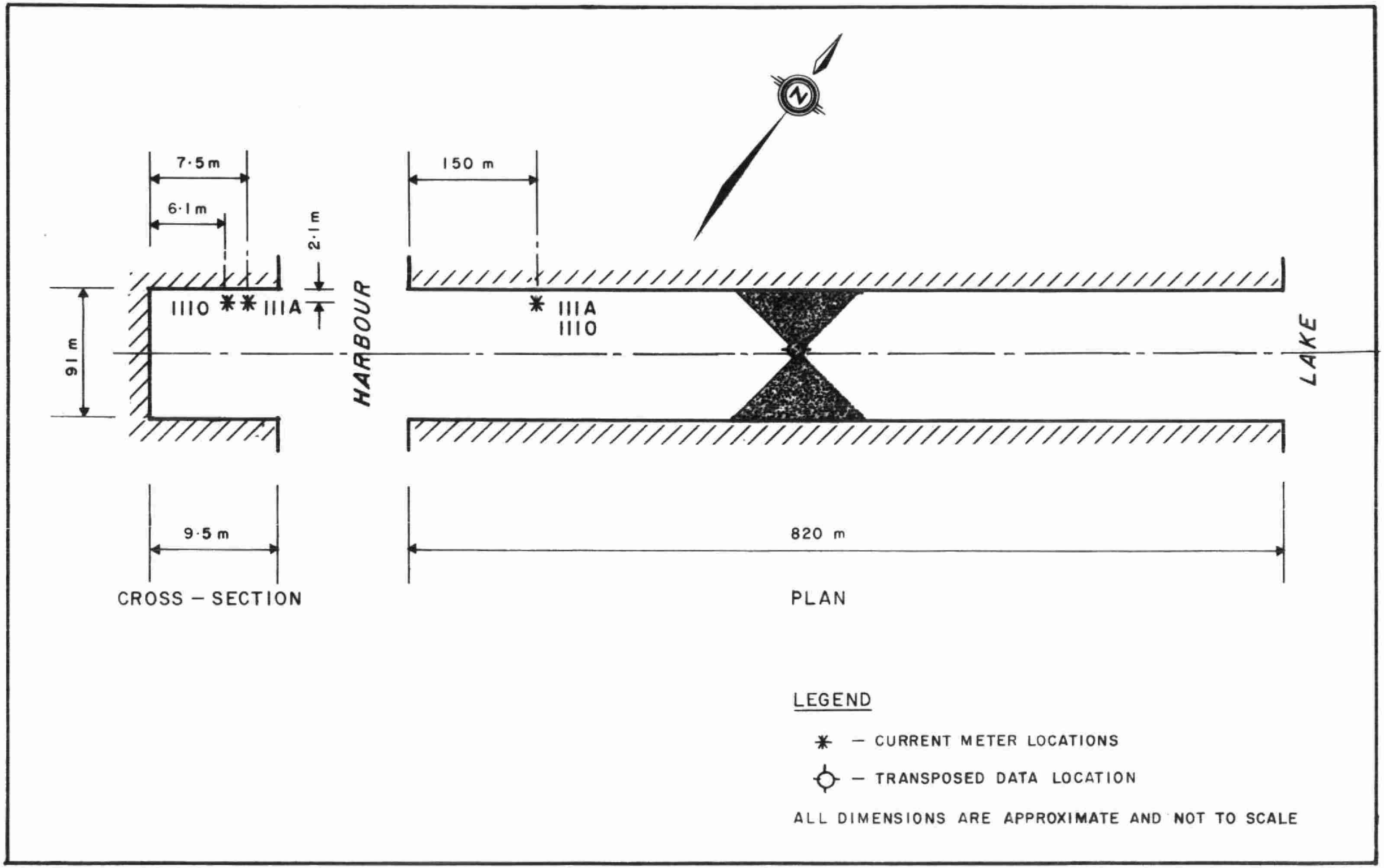


FIGURE 3 : BURLINGTON CANAL

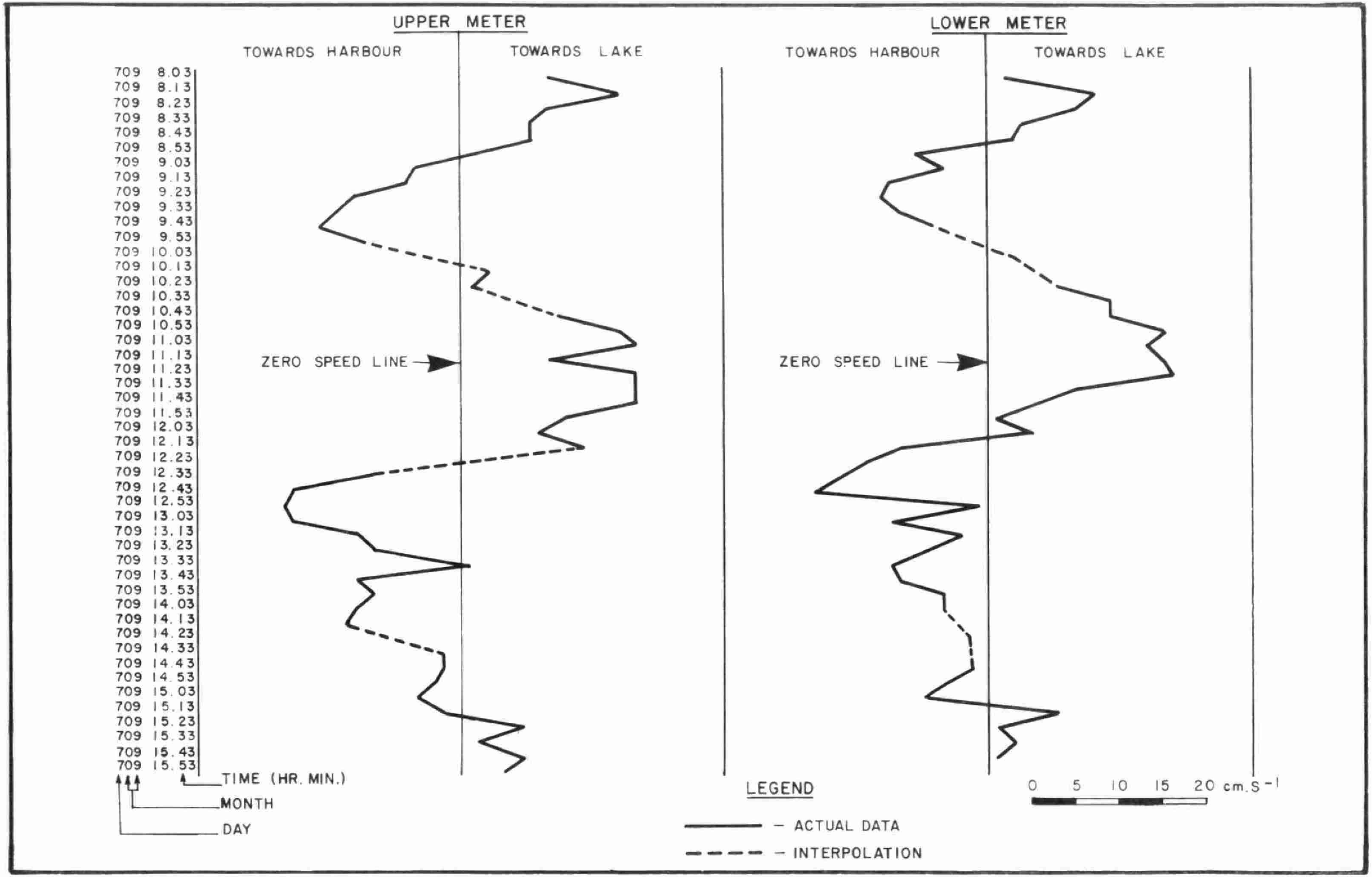


FIGURE 4 : TIME HISTORY OF CURRENTS RESOLVED ALONG BURLINGTON CANAL, LAKE ONTARIO, 1975

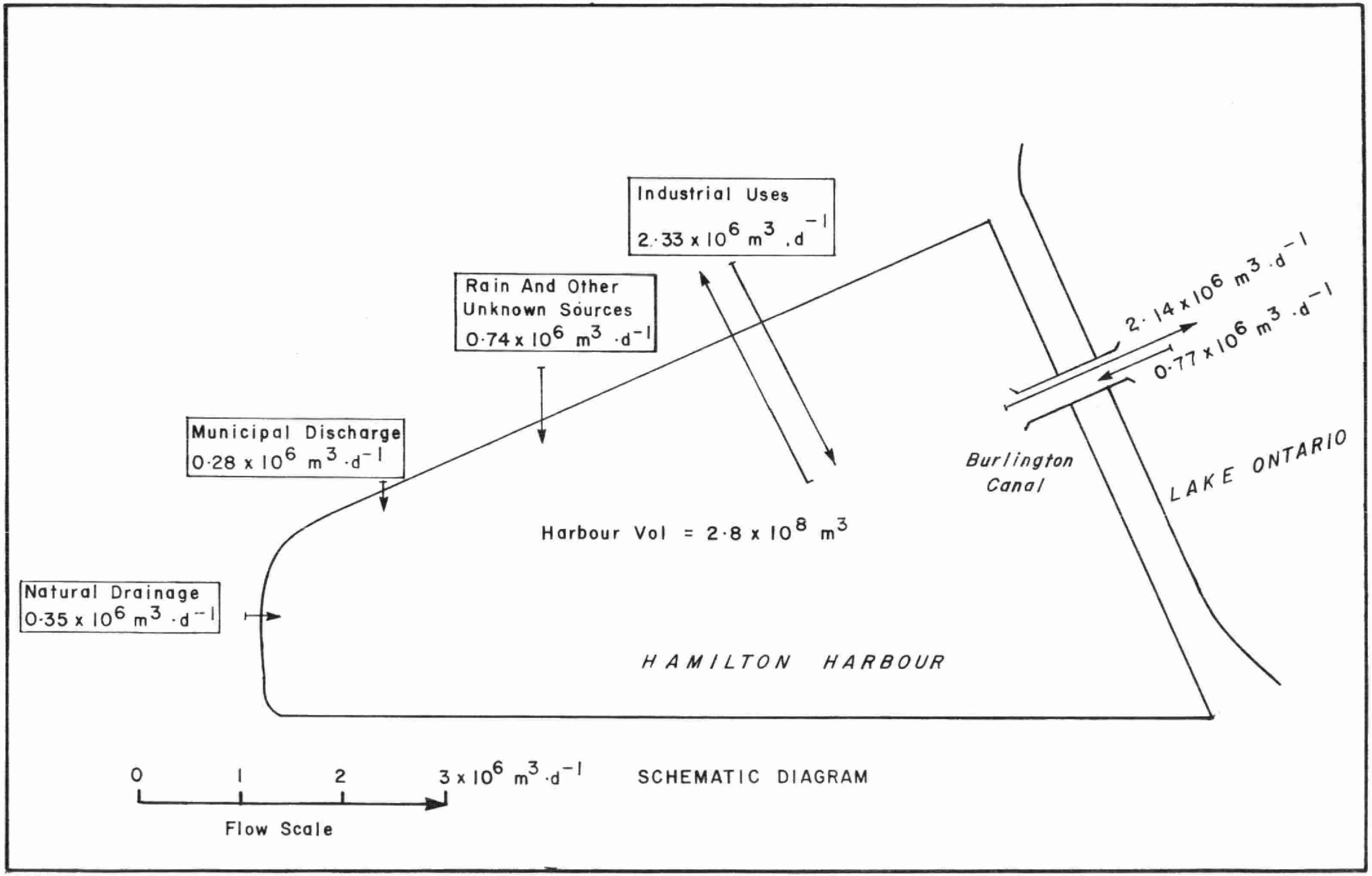


FIGURE 5: MASS BALANCE OF HAMILTON HARBOUR, LAKE ONTARIO 1 – 13 SEPTEMBER, 1975

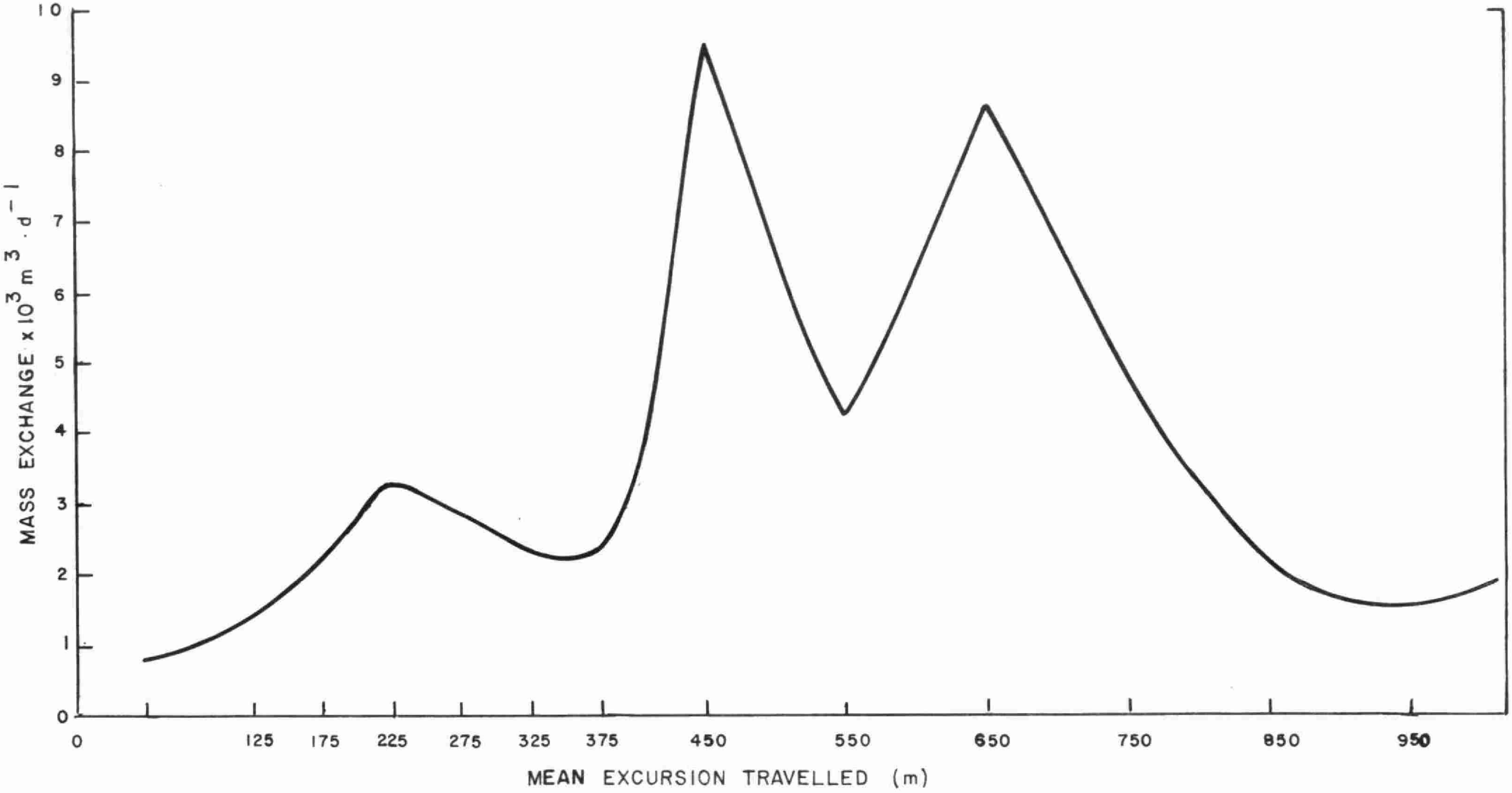


FIGURE 6: MASS EXCHANGE THROUGH BURLINGTON CANAL, LAKE ONTARIO, SEPTEMBER 1975

APPENDIX

Two-dimensional frequency of occurrence of current speed and direction for the two levels are presented in Tables 1.01 and 1.02.

Table 1.03 shows the detailed computational procedure for mass exchange.

The temperature profiles (based on recorded values) every two hours are presented in Figure 1.01 for September 5, 1975.

Figures 1.02 and 1.03 display the dissolved solid profiles in the harbour on August 15 and September 16, 1975. The estimate of DS content of the harbour was based on these profiles.

TABLE 1.01

LOCATION CODE : 111A
AREA : BURLINGTON CANAL
LAKE : ONTARIO

PERIOD : SEP 75
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES									
SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0 -- 0.30	0.33	0.38	4.92	0.38	0.61	0.98	12.51	0.20	20.30
0.31 -- 2.99	0.43	0.71	5.02	0.38	1.16	1.13	5.88	0.43	15.13
3.00 -- 5.99	0.81	0.58	4.69	0.13	0.61	1.19	5.80	0.40	14.20
6.00 -- 8.99	0.25	0.25	4.89	0.18	0.25	0.78	6.20	0.23	13.04
9.00 -- 11.99	0.0	0.05	3.13	0.23	0.30	0.25	5.30	0.10	9.36
12.00 -- 14.99	0.08	0.13	2.47	0.03	0.10	0.43	4.92	0.03	8.17
15.00 -- 44.99	0.0	0.13	4.36	0.03	0.08	0.20	15.01	0.0	19.80
COLUMN SUMS	1.89	2.22	29.48	1.34	3.10	4.97	55.61	1.39	100.00

RESULTANT CURRENT IS 3.27 CM/S AT 252 DEG FROM NORTH

TOTAL NO. READINGS 3965

MEAN CURRENT IS 8.23 CM/S

PERSISTENCE IS 0.40

MAXIMUM CURRENT IS 44.94 CM/S

READINGS TAKEN EVERY 10 MIN

METER OPERATED AT 7.5 M FROM BOTTOM IN 9.4 M OF WATER

TABLE 1.02

LOCATION CODE : 1110
AREA : BURLINGTON CANAL
LAKE : ONTARIO

PERIOD : SEP 75
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

	DIRECTION (COMING FROM) IN DEGREES								
SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	1.02	6.36	0.97	2.00	2.30	3.13	2.74	0.97	19.49
0.31 -- 2.99	0.97	5.08	1.83	1.53	1.53	2.72	3.62	0.81	18.10
3.00 -- 5.99	0.44	4.06	2.07	1.04	0.63	3.90	2.62	0.49	15.25
6.00 -- 8.99	0.30	3.83	1.44	0.37	0.21	3.13	2.67	0.12	12.07
9.00 -- 11.99	0.02	2.83	1.28	0.09	0.07	1.81	2.76	0.14	9.00
12.00 -- 14.99	0.02	2.37	0.60	0.07	0.02	1.55	2.58	0.0	7.22
15.00 -- 44.99	0.0	4.71	1.49	0.05	0.05	4.57	8.01	0.0	18.87
COLUMN SUMS	2.78	29.24	9.68	5.15	4.80	20.82	24.99	2.53	100.00

RESULTANT CURRENT IS 1.76 CM/S AT 255 DEG FROM NORTH

TOTAL NO. READINGS 4309

MEAN CURRENT IS 7.94 CM/S

PERSISTENCE IS 0.22

MAXIMUM CURRENT IS 44.23 CM/S

READINGS TAKEN EVERY 10 MIN

METER OPERATED AT 6.1 M FROM BOTTOM IN 9.4 M OF WATER

TABLE 1.03: Detailed Computation of Mass Exchange between Hamilton Harbour and Lake Ontario, 1975

Sept 75	Start Time	TO HARBOUR UPPER i	u_1	x_1	TO HARBOUR LOWER i	u_1	x_1	TO HARBOUR AVG i	$\bar{u}_1$	$\bar{x}_1$	TO LAKE UPPER i	u_2	x_2	TO LAKE LOWER i	u_2	x_2	TO LAKE AVG i	$\bar{u}_2$	$\bar{x}_2$	TO HARBOUR q_1	TO LAKE q_2
1	1.23										18	6	648	21	5	630	19.5	5.5	639		656
	4.53	8	3	144	6	2	72	7.0	2.5	108										107	
	6.13										7	4	168	0	0	0	7.0	4.0	168		171
	6.33	6	3	108	11	5	330	8.5	4.0	219										208	
	8.43	7	5	210	7	5	210	7.0	5.0	210										214	
	9.43										10	4	240	8	8	384	9.0	6.0	312		330
	11.23	8	5	240	8	5	240	8.0	5.0	240										245	
	12.53										10	7	420	10	6	360	10.0	6.5	390		398
	14.43	10	3	180	9	3	162	9.5	3.0	171										174	
	16.03										12	7	504	10	6	360	11.0	6.5	432		438
	18.43										9	5	270	9	6	324	9.0	5.5	297		301
	20.23										13	5	390	10	4	240	11.5	4.5	315		303
2	1.23										11	8	528	10	7	420	10.5	7.5	474		482
	6.23										10	9	540	8	6	288	9.0	7.5	414		413
	10.23										6	7	252	7	4	168	6.5	5.5	210		219
	12.53										13	6	468	7	5	210	10.0	5.5	339		337
	16.43										9	9	486	10	6	360	9.5	9.5	423		552
	22.33	9	8	432	8	9	432	8.5	8.5	432										442	
3	0.03										9	11	594	9	14	756	9.0	12.5	675		689
	1.23	10	9	540	9	9	486	9.5	9.0	513										523	
	3.03										13	13	1014	13	11	858	13.0	12.0	936		955
	7.43	4	4	96	8	4	192	6.0	4.0	144										147	
	8.23										14	10	840	11	8	528	12.5	9.0	684		689
	10.43	15	8	720	16	8	768	15.5	8.0	744										759	
	13.23										13	7	546	12	7	504	12.5	7.0	525		536
	15.43	7	7	294	8	3	144	7.5	5.0	219										230	

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... $x10^3$ m^3

TABLE 1.03: Cont'd

Sept 75	Start Time	TO HARBOUR: UPPER i	u_1	x_1	LOWER i	u_1	x_1	AVG i	$\bar{u}_1$	$\bar{x}_1$	TO LAKE: UPPER i	u_2	x_2	LOWER i	u_2	x_2	AVG i	$\bar{u}_2$	$\bar{x}_2$	TO HARBOUR q_1	TO LAKE q_2
3	16.43										7	7	294	6	4	144	7.5	5.5	219		252
	19.13										11	8	528	9	8	432	10.0	8.0	480		490
	23.13	6	9	324	7	6	252	6.5	7.5	288										318	
4	0.43	15	5	450	15	5	450	15.0	5.0	450										459	
	3.03										6	6	216	6	3	108	6.0	4.5	162		165
	4.23										8	10	480	7	8	336	7.5	9.0	408		413
	6.13										7	10	420	7	8	336	7.0	9.0	378		386
	7.13	5	6		9	4		7.0	5.0	210										214	
	8.13										16	8	768	9	8	432	12.5	8.0	600		612
	12.13	9	8	432	6	5	180	7.5	6.5	306										298	
	14.33										16	7		16	4		16.0	5.5	528		539
	17.13										29	3	522	29	4	696	29.0	3.5	609		621
	22.33	5	4		9	7		7.0	5.5	231										236	
	23.23										8	5		6	3		7.0	4.0	168		171
5	0.53	12	5	360	12	5	360	12.0	5.0	360										367	
	2.53										16	6	576	15	3	270	15.5	4.5	423		427
	5.23	11	1		13	2		12.0	1.5	108										110	
	7.33										21	5		19	4		20.0	4.5	540		550
	11.03	23	4	552	23	6	828	23.0	5.0	690										704	
	15.13										14	7		11	6		12.5	6.5	488		497
	17.03	6	3		9	4		7.5	3.5	158										161	
	18.23										8	7		4	2		6.0	4.5	162		165
	19.53										12	6	432	14	4	336	13.0	5.0	384		398
	22.03	8	7		6	4		7.0	5.5	231										236	
6	0.13	8	9	432	8	9	432	8.0	9.0	432										441	
	1.23										10	8	480	9	10	540	9.5	9.0	510		523
	2.53	5	11		4	8		4.5	9.5	257										262	

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... x 10^3 m^3

TABLE 1.03: Cont'd

		TO HARBOUR									TO LAKE									TO	
		UPPER			LOWER			AVG			UPPER			LOWER			AVG			HARBOUR	LAKE
Sept 75	Start Time	i	u_1	x_1	i	u_1	x_1	i	$\bar{u}_1$	$\bar{x}_1$	i	u_2	x_2	i	u_2	x_2	i	$\bar{u}_2$	$\bar{x}_2$	q_1	q_2
6	3.53										20	8	960	20	9	1080	20.0	8.5	1020		1040
	8.23										11	14	924	11	13	858	11.0	13.5	891		909
	10.13	4	5		5	7		4.5	6.0	162										165	
	11.03										4	9		5	9		4.5	9.0	243		248
	12.13	17	5	510	18	8	864	17.5	6.5	687										696	
	15.23										9	8	432	8	8	384	8.5	8.0	408		416
	16.23	7	5		9	7		8.0	6.0	288										293	
	18.03										10	8	480	10	9	540	10.0	8.5	510		520
	19.33	11	4		11	4		11.0	4.0	286										269	
	21.23										10	9	540	9	9	486	9.5	9.0	513		523
	23.13	7	8	336	9	8	432	8.0	8.0	384										367	
7	0.23										10	9	540	12	15	1080	11.0	12.0	810		806
	2.13	14	10	840	13	10	780	13.5	10.0	810										826	
	4.33										8	6		7	4		7.5	5.0	225		230
	5.53	6	6		8	8		7.0	7.0	294										300	
	7.03										11	8	528	10	8	480	10.5	8.0	504		514
	8.53	7	8		7	6		7.0	7.0	294										300	
	10.13										14	9	756	13	9	702	13.5	9.0	729		744
	12.33	17	7	714	18	7	756	17.5	7.0	735										750	
	15.13										10	5		7	4		8.5	4.5	230		234
	16.53	6	2		9	2		7.5	2.0	90										92	
	18.23										3	4		4	3		3.5	3.5	74		75
	19.23	3	3		3	2		3.0	2.5	45										46	
	19.43										16	7	672	16	7	672	16.0	7.0	672		685
	22.23	3	4		3	9		3.0	6.5	117										119	
	23.03	5	5		5	8		5.0	6.5	195										199	

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... x 10^3 m^3

TABLE 1.03: Cont'd

Sept 75	Start Time	TO HARBOUR									TO LAKE									TO	
		UPPER			LOWER			AVG			UPPER			LOWER			AVG			HARBOUR	LAKE
		i	u_1	x_1	i	u_1	x_1	i	$\bar{u}_1$	$\bar{x}_1$	i	u_2	x_2	i	u_2	x_2	i	$\bar{u}_2$	$\bar{x}_2$	q_1	q_2
8	0.13										16	5	480	16	5	480	16.0	5.0	480		490
	2.53	14	5	420	14	8	672	14.0	6.5	546										557	
	5.23										13	12	936	15	9	810	14.0	10.5	873		900
	7.33	8	10		6	9		7.0	9.5	400										407	
	8.33										16	10	960	16	9	864	16.0	9.5	912		930
	11.23	7	5		7	7		7.0	6.0	252										257	
	12.43										6	4		6	6		6.0	5.0	180		184
	13.53	8	5		8	5		8.0	5.0	240										245	
	15.13										7	8	336	8	14	672	7.5	11.0	504		505
	16.23	9	6	324	9	10	540	9.0	8.0	432										441	
	18.23										12	9	648	12	9	648	12.0	9.0	648		661
	21.23										10	12		9	1		9.5	6.5	371		378
	23.23	11	12	792	10	10	600	10.5	11.0	696										707	
9	0.53										9	12	648	9	9	486	9.0	10.5	567		578
	2.23	13	8	624	15	9	810	14.0	8.5	717										728	
	4.53	12	2	144	12	7	504	12.0	4.5	324										330	
	7.03										11	10	660	9	12	648	10.0	11.0	654		673
	8.43	9	4		9	6		9.0	5.0	270										275	
	10.23										19	9	1026	19	5	570	19.0	7.0	798		814
	13.23	10	9	540	9	8	432	9.5	8.5	486										494	
	15.13										20	7		18	4		19.0	5.5	627		640
	18.42	10	5	300	11	9	594	10.5	7.0	447										450	
	20.22										14	7	588	14	5	420	14.0	6.0	504		514
	23.12										25	3		25	2		25.0	2.5	375		382
10	4.22	15	4		15	4		15.0	4.0	360										367	
	6.42										6	4		6	4		6.0	4.0	144		147
	9.22	3	10		5	6		4.0	8.0	192										196	

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... $x\ 10^3\ m^3$

TABLE 1.03: Cont'd

Sept 75	Start Time	TO HARBOUR									TO LAKE									TO	
		UPPER			LOWER			AVG			UPPER			LOWER			AVG			HARBOUR	LAKE
		i	u_1	x_1	i	u_1	x_1	i	$\bar{u}_1$	$\bar{x}_1$	i	u_2	x_2	i	u_2	x_2	i	$\bar{u}_2$	$\bar{x}_2$	q_1	q_2
10	10.02										5	6		6	10		5.5	8.0	264		269
	11.02	7	2		7	2		7.0	2.0	84										86	
	12.02										7	4					7.0	4.0	168		171
	13.32	4	2		4	3		4.0	2.5	60										61	
	14.12										2	4					2.5	4.0	60		61
	14.42	5	3		2	3		3.5	3.0	63										64	
	15.52										4	7		3	4		3.5	5.5	116		118
	16.22	3	3		3	3		3.0	3.0	54										55	
	16.42										8	2		8	1		8.0	1.5	72		73
	18.22	4	5		5	6		4.5	5.5	149										151	
	19.12										7	7		8	8		7.5	7.5	338		344
	20.52										10	6		9	4		9.5	5.0	285		291
	22.42	7	3		8	3		7.5	3.0	135										138	
11	0.02										13	10	780	12	10	720	12.5	10.0	750		765
	2.02	3	9		3	9		3.0	9.0	162										165	
	2.32										5	5		5	5		5.0	5.0	150		153
	3.22	3	6		4	2		3.5	4.0	84										86	
	4.02										5	5		4	6		4.5	5.0	135		138
	4.42	3	7		3	12		3.0	9.5	171										174	
	5.22										4	12		4	10		4.0	11.0	264		269
	6.32										5	9		4	6		4.5	7.5	203		207
	7.22	9	5		10	7		9.5	6.0	342										345	
	9.05										8	10	480	9	8	432	8.5	9.5	456		494
	10.32	10	4		10	3		10.0	3.5	210										214	
	12.22										22	6	792	20	5	600	21.0	5.5	696		707
	16.12	4	6		4	4		4.0	5.0	120										122	
	16.42										3	4		4	2		3.5	3.0	63		64

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... x 10^3 m^3

TABLE 1.03: Cont'd

Sept 75	Start Time	TO HARBOUR									TO LAKE									TO	
		UPPER			LOWER			AVG			UPPER			LOWER			AVG			HARBOUR	LAKE
		i	u_1	x_1	i	u_1	x_1	i	$\bar{u}_1$	$\bar{x}_1$	i	u_2	$\bar{x}_2$	i	u_2	x_2	i	$\bar{u}_2$	$\bar{x}_2$	q_1	q_2
11	17.22	3	6		3	5		3.0	5.5	99										101	
	17.52										20	8	960	18	3	324	19.0	5.5	642		640
	21.32	3	5		6	15		4.5	10.0	270										275	
	22.02										3	4		2	12		2.5	8	120		122
	22.32	3	1		3	9		3.0	5.0	90										92	
	23.12										17	10	1020	19	10	1140	18.0	10.0	1080		1102
12	2.12	2	13		3	9		2.5	11.0	165										168	
	2.22										8	10	480	8	10	480	8.0	10.0	480		490
	4.52	8	10	480	8	8	384	8.0	9.0	432										441	
	6.22										5	12		4	6		4.5	9.0	243		248
	7.12	4	6		5	5		4.5	5.5	149										151	
	7.52										5	6		4	4		4.5	5.0	135		138
	8.42	4	7		5	9		4.5	8.0	216										220	
	9.22										9	6	324	10	10	600	9.5	8.0	462		465
	11.02	10	10	600	12	10	720	11.0	10.0	600										673	
	14.52										13	10	780	12	10	720	12.5	10.0	750		765
	15.52	5	7		9	8		7.0	7.5	315										321	
13	1.32	5	10		4	5		4.5	7.5	203										207	
	3.32										14	9	756	14	8	672	14.0	8.5	714		728
	12.22										14	10	840	17	5	510	15.5	7.5	675		711
	16.22										6	11	396	6	8	288	6.0	9.5	342		342
	21.22										6	10	360	9	10	540	7.5	10.0	450		459

UNITS: i ...... x 10 min
u ...... $cm.s^{-1}$
x ...... m
q ...... $x\ 10^3\ m^3$

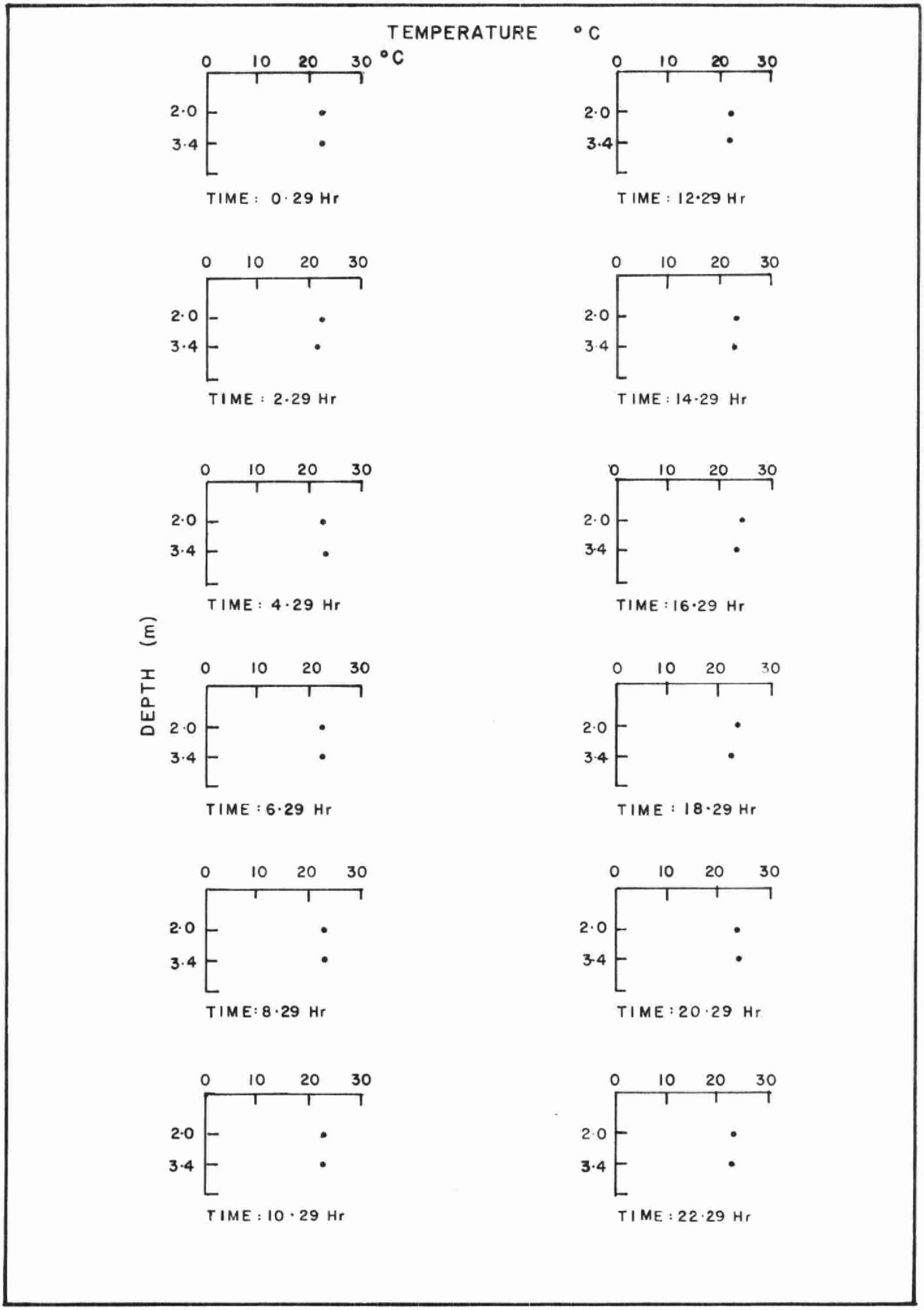


FIGURE 1·01 : TEMPERATURE PROFILES ON 5 th SEPTEMBER 1975
BURLINGTON CANAL, LAKE ONTARIO

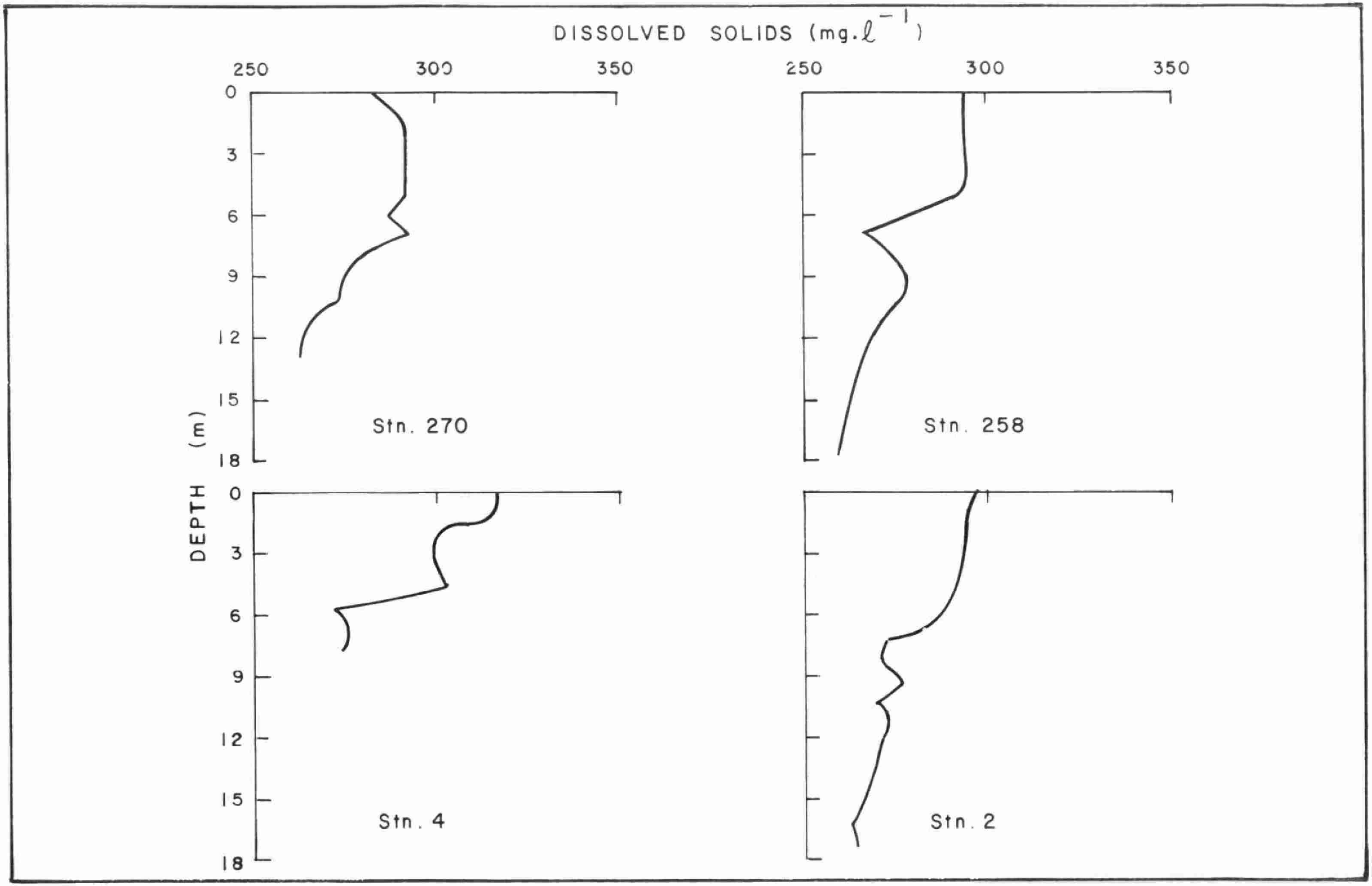


FIGURE 1·02 : DISSOLVED SOLIDS VERTICAL PROFILE, HAMILTON HARBOUR, 15 AUGUST, 1975.

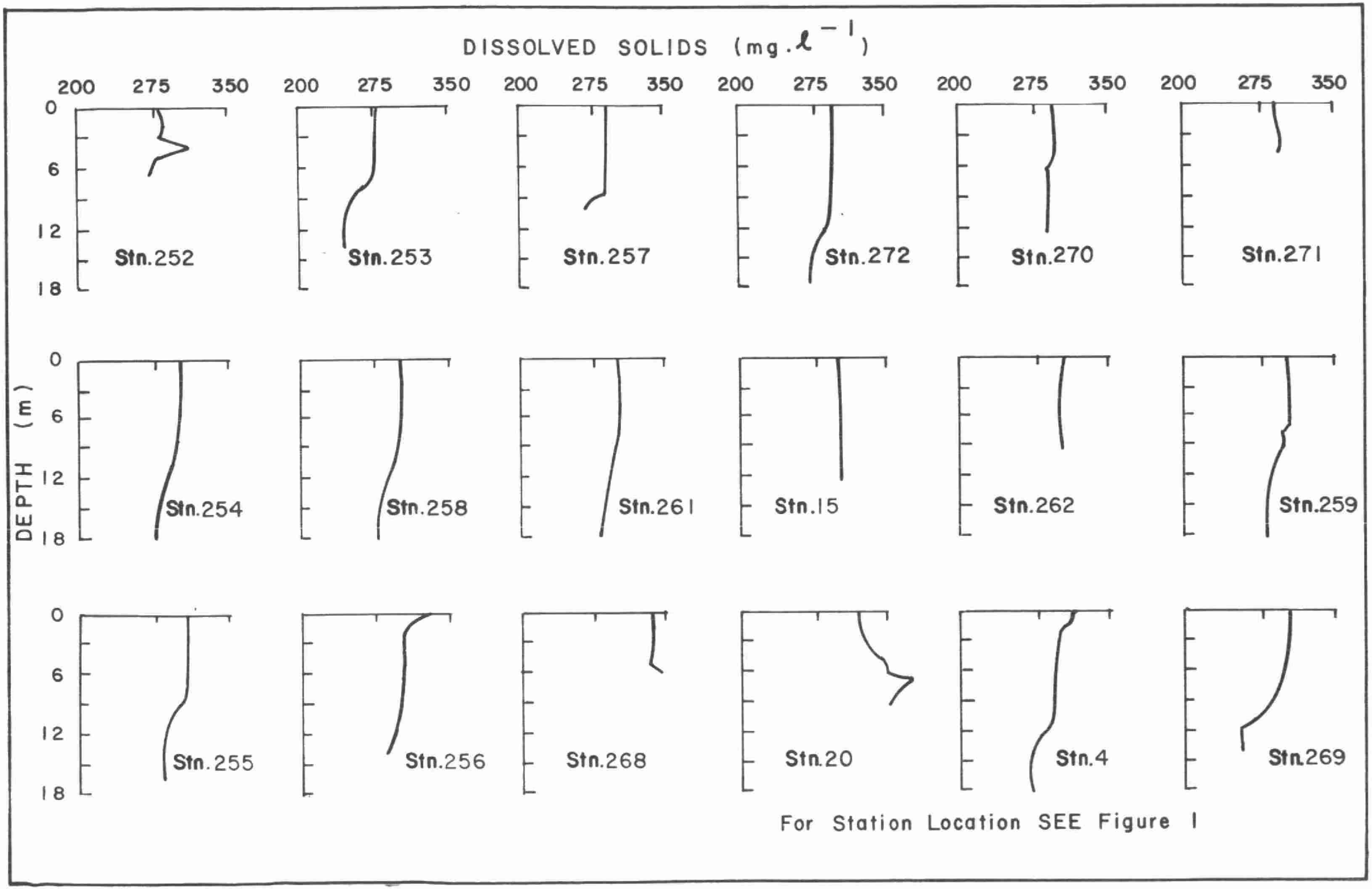


FIGURE 1·03 : DISSOLVED SOLIDS VERTICAL PROFILE, HAMILTON HARBOUR, 16 SEPTEMBER, 1975